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Abstract

Weather forecasts started from realistic initial conditions are used to diagnose the large warm and dry bias over the United States Southern Great Plains simulated by the GFDL climate model. The forecasts exhibit biases in surface air temperature and precipitation within 3 days which appear to be similar to the climate bias. With the model simulating realistic evaporation but underestimated precipitation, a deficit in soil moisture results which amplifies the initial temperature bias through feedbacks with the land surface. The underestimate of precipitation is associated with an inability of the model to simulate the eastward propagation of convection from the front-range of the Rocky Mountains and is insensitive to an increase of horizontal resolution from 2° to 0.5° latitude.

1. Introduction

Two of the most important simulated variables of a climate model are the surface air temperature and precipitation. Climate models exhibit important biases relative to observations in both quantities yet an understanding of the causes of the biases is often lacking. For example, consider the summertime bias in surface air temperature and precipitation over North America (Figures 1a-b) that results when the climate model of the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (GFDL) known as AM2 is integrated with observed sea surface temperatures. Prominent is the overestimation of surface air temperature in the south central United States with peak values in excess of 6K. For precipitation, there are large underestimates along the coast of the Gulf of Mexico and over Florida as well as in the central United States. Over the Southern Great Plains, AM2 simulates about 0.7 mm day^{-1} or 25% of the seasonal mean.

Understanding the cause of this bias in the region of the Southern Great Plains is difficult because of feedbacks between the land surface and atmosphere that are known to be prominent in this and many other models [*Koster et al.*, 2004]. For example, reduced precipitation may result if evaporation is suppressed due to below normal soil moisture. However, below normal precipitation may also be the cause of the below normal soil moisture. Furthermore, below normal soil moisture may lead to above normal surface air temperature as the vegetation resists giving up its moisture and more of the radiative gain of the surface is balanced by sensible instead of evaporative heat loss. Having a means to separate initial errors from amplifying feedbacks would be useful.

For this reason, the approach of weather forecasting is attractive. If the state of the atmosphere and land model can be initialized with observations, it may be possible to diagnose the process behind the drift towards a biased climate [*Phillips et al.*, 2004]. For example, because of the several week timescale associated with soil moisture, it is possible to diagnose errors in precipitation and radiation in a weather forecasting mode before they can cause the soil to loose an appreciable amount of water. Here one month of 3 day weather forecasts with AM2 are examined and compared to observations from the Atmospheric Radiation Measurement program [*Ackerman and Stokes*, 2003] at its Southern Great Plains site to understand AM2's bias in temperature and precipitation.

2. Observations and procedures

2.1 ARM Observations

The period of simulation coincides with an intensive observing period conducted by ARM from 19 June to 17 July 1997. Observations available include those of surface radiation, sensible and latent heat fluxes, surface air temperature and other meteorology from about two dozen stations. Surface precipitation is inferred from radar observations. Estimates of the vertical profile of clouds are retrieved from the cloud radar and lidar at the ARM central facility. Estimates of clouds and the top-of-atmosphere (TOA) radiation budget from geostationary satellite observations are also available. All observations are averaged over an area within a circle of diameter 360 km centered on the ARM central facility at 36°N 97°W.

2.2 AM2 and weather forecast methods

AM2 is a climate model with horizontal resolution of 2.0° latitude by 2.5° longitude and 24 vertical levels; convection is represented with the Relaxed-Arakawa Schubert parameterization. Further details are available from *GFDL GAMDT* [2004]. Three day weather forecasts with AM2 are started every day in the period at 00Z, 06Z, 12Z, and 18Z; but since results are not highly sensitive to the starting hour, the results from the 00Z forecasts are emphasized. For temperature, water vapor specific humidity, horizontal winds, and surface pressure, AM2 is initialized with ERA-40 reanalysis data from the European Centre for Medium Range Weather Forecasts [*Simmons and Gibson*, 2000]. The analysis is transformed to the native grid of AM2 accounting for its representation of the surface orography [*Boyle et al.*, 2005]. No data assimilation is performed. Root-mean square errors of ERA-40 relative to ARM observations in this period are less than 1K for temperature and approximately 50% of the temporal standard deviation of moisture [*Xie et al.*, 2004]. The land model is initialized with output of a separate 'stand-alone' integration driven with the history of surface air temperature, winds, humidity and radiation from ERA-40 supplemented by observed daily mean precipitation.

Results from hours 12 to 36 of each forecast are emphasized since it is in this time range that the model has past the initials shocks due to the use of a foreign analysis but that the model's large-scale state has not diverged strongly from observations. Results are interpolated to the ARM site using distance-weighted averaging of data from the 4 closest grid-boxes.

3. Results

3.1 Weather forecast biases

A weather forecasting approach can be useful in diagnosing a climate bias if the forecasts show evidence of the bias. In forecasts hours 12 to 36, AM2 overestimates the surface air temperature primarily through too large daily maxima. The deviation from observation is ~2K early in the period and ~5K late in the period (Figure 2a). Averaged over the entire period, AM2's bias is 3.2K – a bias of the same sign as is AM2's climate but only ~50% of its amplitude. For precipitation (Figure 2b), AM2 exhibits a serious underestimate similar to its climate with only 1.3 mm day^{-1} averaged over the period compared to 4.0 mm day^{-1} in ARM observations. The timing of the events that the model does simulate is not too bad – the events on 23 June, 26 June, and 4 July are well predicted in time. However, not only is precipitation too small in the events that do occur but some events are missed entirely. A dry bias of 1 g kg^{-1} in surface moisture in ERA-40 may partly cause the lack of precipitation at the end of the period.

To confirm the large-scale nature of errors, Figures 1c-d display the temperature and precipitation errors over North America from forecast hours 0 to 24. Positive forecast temperature biases occur over the central United States in a pattern somewhat similar to the climate bias but with reduced amplitude. For precipitation the similarity between forecast and climate biases is greater with common features that include underestimates of precipitation over Florida, the Gulf Coast, and the central United States. This suggests that the reasons for the precipitation error over North America in summer are strong enough that they are not hidden by any adjustments of AM2 to the analysis of a different model.

3.2 Surface energy balance

Examination of the surface energy balance may help to understand why approximately 50% of the climate bias in temperature is present by hours 12 to 36. Averaged over the period, AM2 overestimates the shortwave radiation absorbed by the surface by 43 W m^{-2} (Table 1). The shortwave error is 23 W m^{-2} larger on wet days relative to dry days, suggesting that AM2's lack of precipitation-generating processes also results in an underestimate of clouds and their radiative effects. Satellite data also shows that the bias of TOA shortwave radiation is larger on wet days, while there is little bias on dry days. The differences between the surface and TOA shortwave budget suggest an underestimate of the amount of solar radiation absorbed within the atmosphere – perhaps due to an underestimate of absorbing aerosol. For outgoing longwave radiation, the model error is also greater on wet days. Comparison of AM2's cloud amounts to both satellite and ARM cloud radar observations provides direct evidence that the model underestimates the amount of cloud on both wet and dry days with a larger error on wet days.

AM2's overestimate of the surface net shortwave radiation is balanced by a corresponding large overestimate in the sensible heat flux with smaller differences in the latent and surface net longwave heat fluxes. The ARM observations of sensible and latent heat flux might contain biases because of biased sampling of the region's surface types. However, prior work suggests that the biases are about 10 W m^{-2} for a multi-week summertime average [*Doran et al.*, 1998], smaller than the differences between AM2 and the observations.

Consequently, a plausible explanation is that too much heating of the surface by solar radiation may cause AM2's anomalously large daytime surface temperatures in the first 36 forecast hours. The larger than observed surface temperature would then promote larger than observed sensible heat flux and net longwave cooling. Consistent with this hypothesis, the surface air temperature bias is somewhat larger on wet days (3.5K vs. 2.8K) as is the surface solar radiation bias.

3.3 Climate drift

Because only 50% of the climate bias in surface temperature is present by forecast hours 12 to 36, further increases in the bias must appear at later forecast times. Figure 3a shows the 24-hour running mean surface air temperature from the observations and hours 0 to 24, 24 to 48, and 48 to 72 of the forecasts. A warm bias of 2.2K present in the first 24 hours grows to 4.1K in day 3 forecasts.

The growth of the temperature bias appears to be due to positive feedbacks with the land-surface. Since evaporation in the AM2 forecasts is fairly close to observed, the underestimate of precipitation leads to strong reductions in soil moisture (Figure 3b). The mean soil moisture is 11.5 kg m^{-2} on forecast day 3 as compared to 14.0 kg m^{-2} on day 1. The consequence of a drier soil is a reduction of the ability of the surface to use solar heating to evaporate water. Instead, solar heating is used to raise the surface temperature.

To display the connection between surface temperature and soil moisture, the forecast which began on 19 June is integrated for 30 days (short-long dashed lines in Figure 3). AM2 looses so much soil moisture that by 5 July there is no water left in the soil. This is consistent with the 14 days needed for the 2.2 mm day^{-1} bias in precipitation minus evaporation to deplete the 30 mm of soil moisture present at the start of the period. About this time, the overestimate of surface air temperature grows to in excess of 8K. For precipitation, this integration yields only 0.3 mm day^{-1} and no 3-hour period after 1 July has a precipitation rate in excess of 1 mm day^{-1}. The reduction of precipitation in this single integration relative to that in forecast hours 12 to 36 is consistent with the positive feedbacks between soil moisture and precipitation diagnosed in this region by *Koster et al.* [2004].

3.4 Diurnal aspects of precipitation variability

The hours of peak precipitation for the three largest precipitation events that occur on 24, 26, and 30 June (Fig. 2) are 3 am, 3 am, and 9 pm local time, respectively. Indeed, the nocturnal maximum of summer precipitation is a unique feature of the U. S. Great Plains [*Dai et al.*, 1999]. A composite diurnal cycle of ARM observations for this period displays a strong nocturnal peak, whereas the forecasts with AM2 show little diurnal variability with too little precipitation at all hours of the day (not shown).

An aspect of the nocturnal maximum in precipitation is that it appears to be associated with coherent eastward propagating convective episodes [*Carbone et al.*, 2002]. These episodes are initiated near sunset by convection over the eastern edge of the U. S. Rocky Mountains (near 105°W). The convection then propagates eastward reaching the longitude of the ARM Southern Great Plains site (96°W) near 3 am local time. Visual inspection of geostationary satellite infrared imagery suggests that the precipitation events on 24, 26, and perhaps 30 June were associated with propagating episodes.

Climatological aspects can be displayed by plotting latitudinal averaged precipitation as a function of time of day and longitude. Figure 4b illustrates the composite of 25 years of May to August precipitation from the North American Regional Reanalysis (NARR) [*Mesinger et al.*, 2006]. Composites based upon radar observations of precipitation show similar features. AM2 composites (Figure 4c) lack propagating episodes although convection at sunset is present at the eastern edge of the Rocky Mountains. This convection is a response to upslope flow and ascent which is induced by diurnal heating over sloped terrain; these large-scale features and the associated low-level jet over the

Southern Great Plains are represented well by AM2 [*Jiang et al.*, 2006a].

One possible cause for the underestimate of nocturnal precipitation in AM2 is that the horizontal resolution of the model is too coarse. However, short-range weather forecasts for this period with 1° resolution did not increase precipitation. Furthermore, climate integrations of AM2 at 1° and 0.5° resolution exhibit no reduction in the Southern Great Plains bias of surface temperature and precipitation (not shown). At 0.5° resolution, more precipitation occurs at the edge of the Rockies with weak hints of propagation but no downstream development (Figure 4d). This suggests that either the physics is in error, or that even finer resolution is needed, or both.

4. Discussion

The overestimate of surface air temperature and underestimate of precipitation that the GFDL climate model AM2 simulates over the Southern Great Plains is present in only the first few days of its weather forecasts started with the model. The initial overestimate of surface temperature appears to be due to an overestimate of surface solar radiation. The primary difference between AM2's forecasts and its climate integrations is that the temperature bias is smaller in the forecasts. The larger temperature bias in climate results from the land-surface feedbacks that are the consequence of the underestimate of precipitation. Thus forecasts have shown that the precipitation bias is not primarily the result of land surface feedbacks but is mostly present before these feedbacks can operate.

Without increased precipitation, the simulation of summertime climate over the

Great Plains in the GFDL climate model will continue to exhibit a detrimental warm bias. Effort should be focused on the simulation of the propagating episodes which appear to contribute the majority of nocturnal precipitation [*Jiang et al.*, 2006b]. Prior research with regional models that have resolution finer than 0.5° latitude indicates that the simulation of propagating episodes can be quite difficult and sensitive to the convection parameterization [*Davis et al.*, 2003; *Liang et al.*, 2004]. At the lower resolution of climate models, models with the correct phase to the diurnal cycle tend to significantly underestimate the amount of precipitation [*Zhang*, 2003; *Xie et al.*, 2004]. Tests of AM2 at 1 and 2° resolutions with modified or alternate convection parameterizations not detailed here do not significantly increase nocturnal precipitation. One possibility is that the lack of AM2's omission of parameterized downdrafts and associated cold pool dynamics (which has not been tested) is at fault. Further work is needed to understand the reasons for AM2's underestimate of precipitation.

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References

Ackerman, T. P. and G. Stokes (2003), The Atmospheric Radiation Measurement program, *Physics Today*, *56*, 38-45.

Boyle, J. S. and 8 co-authors (2005), Diagnosis of Community Atmospheric Model 2 (CAM2) in numerical weather forecast configuration at the Atmospheric Radiation Measurement sites, *J. Geophys. Res.*, *110*, D15S15, doi:10.1029/2004JD005042.

Dai, A., Giorgi, F., and K. E. Trenberth (1999), Observed and model simulated precipitation diurnal cycle over the contiguous United States, *J. Geophys. Res.*, *104*, 6377-6402.

Carbone, R. E. and 3 co-authors (2002), Inferences of predictability associated with warm season precipitation episodes, *J. Atmos. Sci.*, *59*, 2033-2056.

Davis, C. A. and 4 co-authors (2003), Coherence of warm-season continental rainfall in numerical weather prediction models, *Mon. Weather. Rev.*, *131*, 2667-2679.

Doran, J. C. and 6 co-authors (1998), A technique for determining the spatial and temporal distributions of surface fluxes of heat and moisture over the Southern Great Plains Cloud and Radiation Testbed, *J. Geophys. Res.*, *103*, D6, 6109-6121.

The GFDL Global Atmospheric Model Development Team (2004), The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations, *J. Clim.*, *17*, 4641-4673.

Huffman, G. J. and 9 co-authors (1997), The Global Precipitation Climatology Project (GPCP) combined precipitation dataset, *Bull. Am.. Meteorol. Soc.*, *78*, 5-20.

Jiang, X. and 3 co-authors (2006a), AGCM simulated Great-Plains low-level jet and its mechanisms, *J. Atmos. Sci.*, in press.

Jiang, X., N.-C. Lau, and S. A. Klein (2006b), Role of eastward propagating convection systems in the diurnal cycle and seasonal mean of summertime rainfall over the U. S. Great Plains. Submitted to *Geophys. Res. Lett*.

Koster, R. D. and 24 co-authors (2004), Regions of coupling between soil moisture and precipitation, *Science*, *305*, 1138-140.

Liang, X.-Z. and 3 co-authors (2004), Regional climate model simulation of summer precipitation diurnal cycle over the United States, *Geophys. Res. Lett.*, *31*, L24208, doi:10.1029/2004GL021054.

Mesinger, F. and 18 co-authors (2006), North American Regional Reanalysis, *Bull. Am. Meteorol. Soc.*, *87*, 343–360.

Phillips, T. J. and 9 co-authors (2004), Evaluating parameterizations in GCMs: Climate simulation meets weather prediction, *Bull. Am. Meteorol. Soc.*, *85*, 1903-1915.

Simmons, A. J. and J. K. Gibson (2000), The ERA-40 project plan, *Tech. Rep. ERA-40, Project Rep. Ser. 1*, European Centre for Medium-range Weather Forecasts, Reading, United Kingdom.

Xie, P. and P. A. Arkin (1997), Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs, *Bull. Am. Meteorol. Soc.*, *78*, 2539-2558.

Xie, S. and 5 co-authors (2004), Impact of a revised convective triggering mechanism on Community Atmosphere Model, Version 2, simulations: Results from short-range weather forecasts, *J. Geophys. Res.*, *109*, D14102, doi:10.1029/2004JD004692.

Zhang, G. (2003), Roles of tropospheric and boundary layer forcing in the diurnal cycle of convection in the U. S. southern great plains, *Geophys. Res. Lett.*, 30, 2281, doi:10.1029/2003GL018554.

Table 1

Components of the surface and TOA energy budgets for the period 19 June to 17 July from ARM observations ("Obs") and hours 12 to 36 of AM2 forecasts. The wet periods are defined as the four intervals of 00Z 23 June to 00Z 1 July, 12Z 3 July to 00Z 5 July, 00Z 9 July to 12Z 12 July, and 00Z 15 July to 00Z 17 July. The dry periods are all of the non-wet periods between 19 June and 17 July.

Component (W m^{-2})	All Periods		Wet Periods		Dry Periods	
Surface Energy Budget	*Obs*	*AM2*	*Obs*	*AM2*	*Obs*	*AM2*
Sensible Heat Flux	36	81	36	82	36	80
Latent Heat Flux	114	99	108	98	120	100
Net Shortwave Radiation	228	271	210	265	247	279
Net Longwave Radiation	-64	-81	-56	-76	-73	-87
TOA Energy Budget						
Net Shortwave Radiation	365	383	349	378	385	388
Outgoing Longwave Radiation	263	276	246	268	283	285

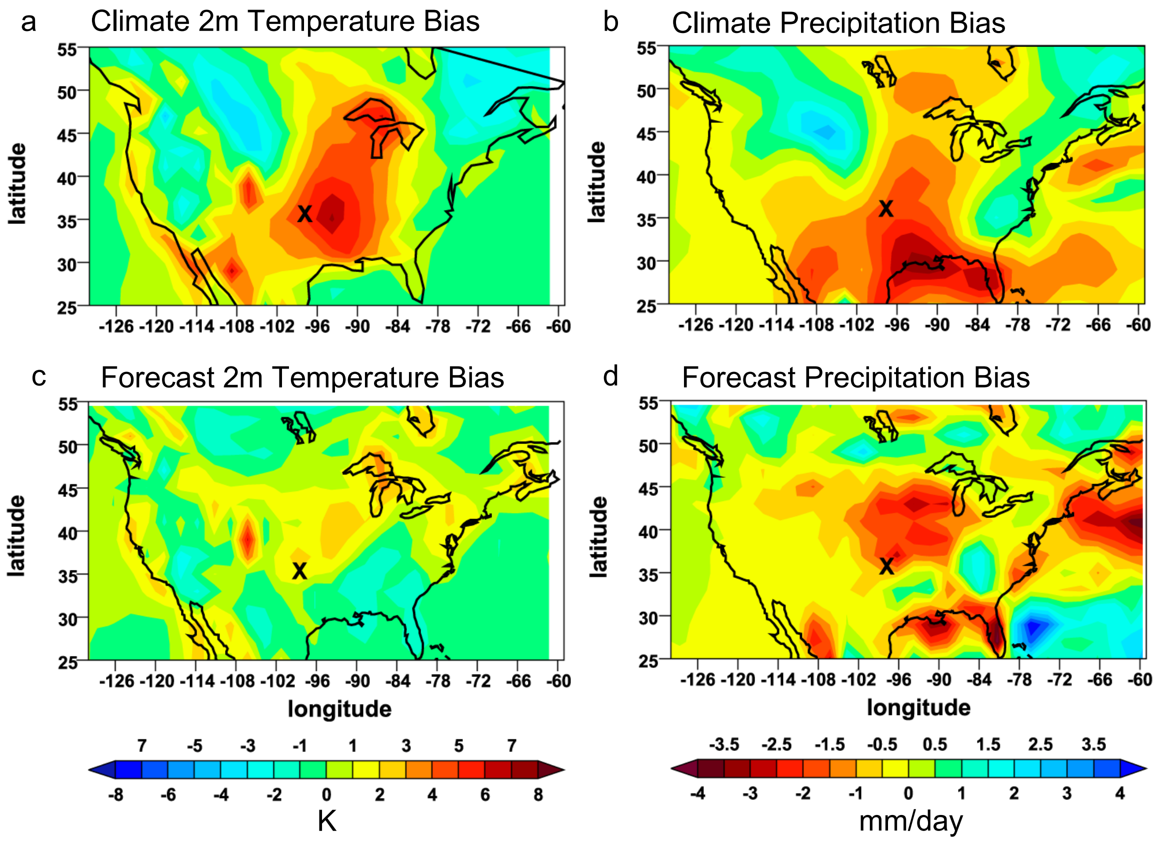

Figure 1. (a and b) The climate bias (model minus observation) for June-July-August 2-meter temperature and precipitation of AM2. Observations are from NARR [*Mesinger et al.*, 2006) for temperature and *Xie and Arkin* [1997] for precipitation. The symbol "X" indicates the location of the ARM Southern Great Plains site. (c and d) The forecast bias for 2-meter temperature and precipitation of AM2 forecasts for hours 0 to 24 for the period 19 June to 17 July 1997. Observations are from the NARR for temperature and GPCP for precipitation [*Huffman et al.*, 1997].

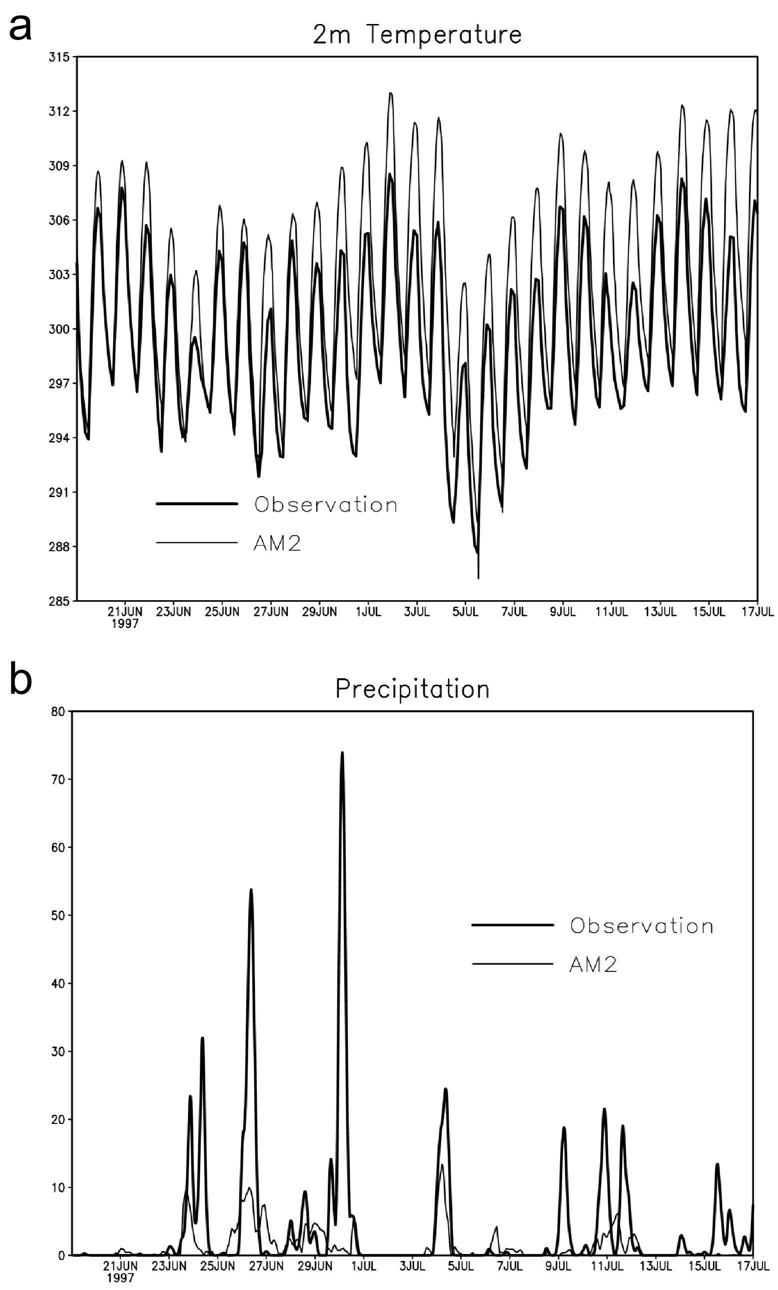

Figure 2. Temperature at 2 meters (a, units: Kelvin) and precipitation (b, units: mm day^{-1}) from ARM observations (thick lines) and hours 12 to 36 of AM2 forecasts (thin lines) at the Southern Great Plains site.

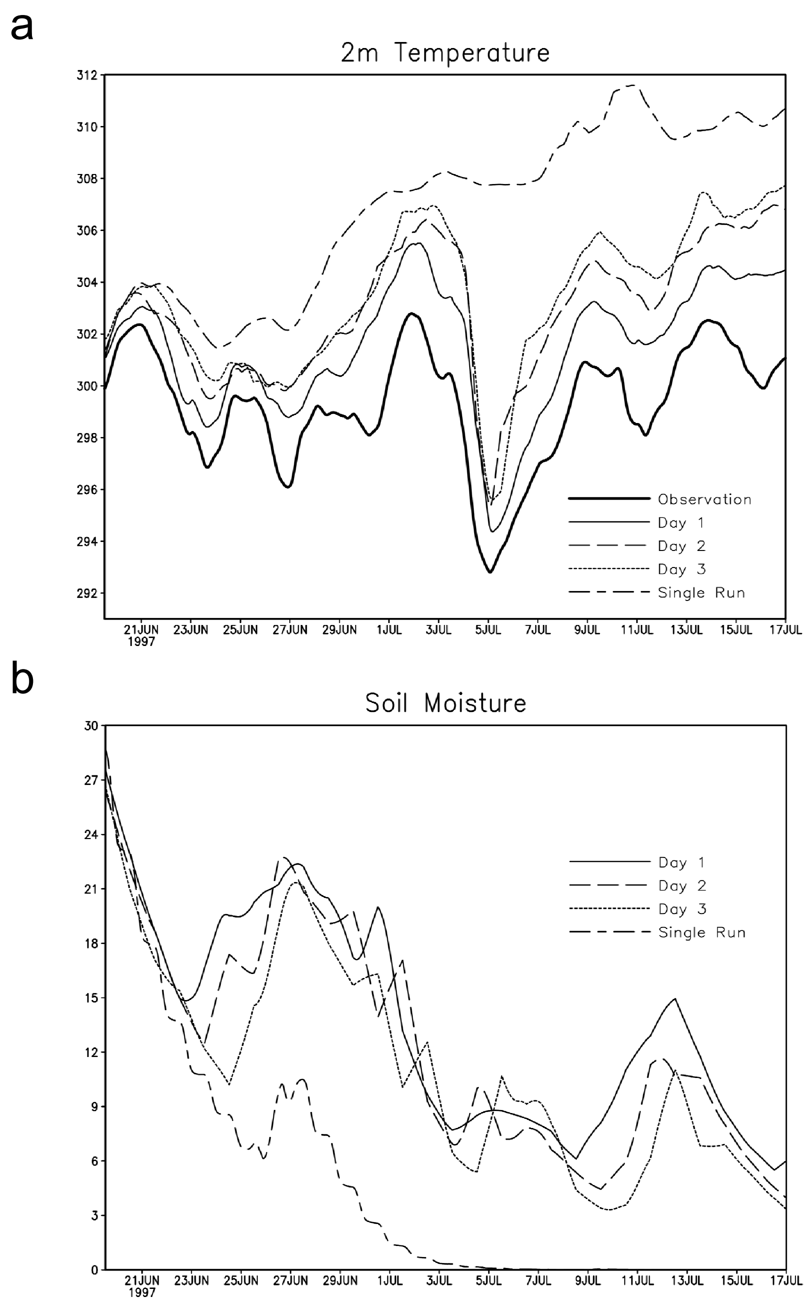

Figure 3. 24-hour running mean temperature (a, units: Kelvin) and soil moisture (b, units: kg m^{-2}) from ARM observations (thick line) and AM2 forecasts for hours 0 to 24 (solid line), hours 24 to 48 (dashed line), and hours 48 to 72 (dotted line) at the Southern Great Plains site. Also shown are the temperature and soil moisture from a single 30 day forecast which begins on 19 June (short-long dashed line).

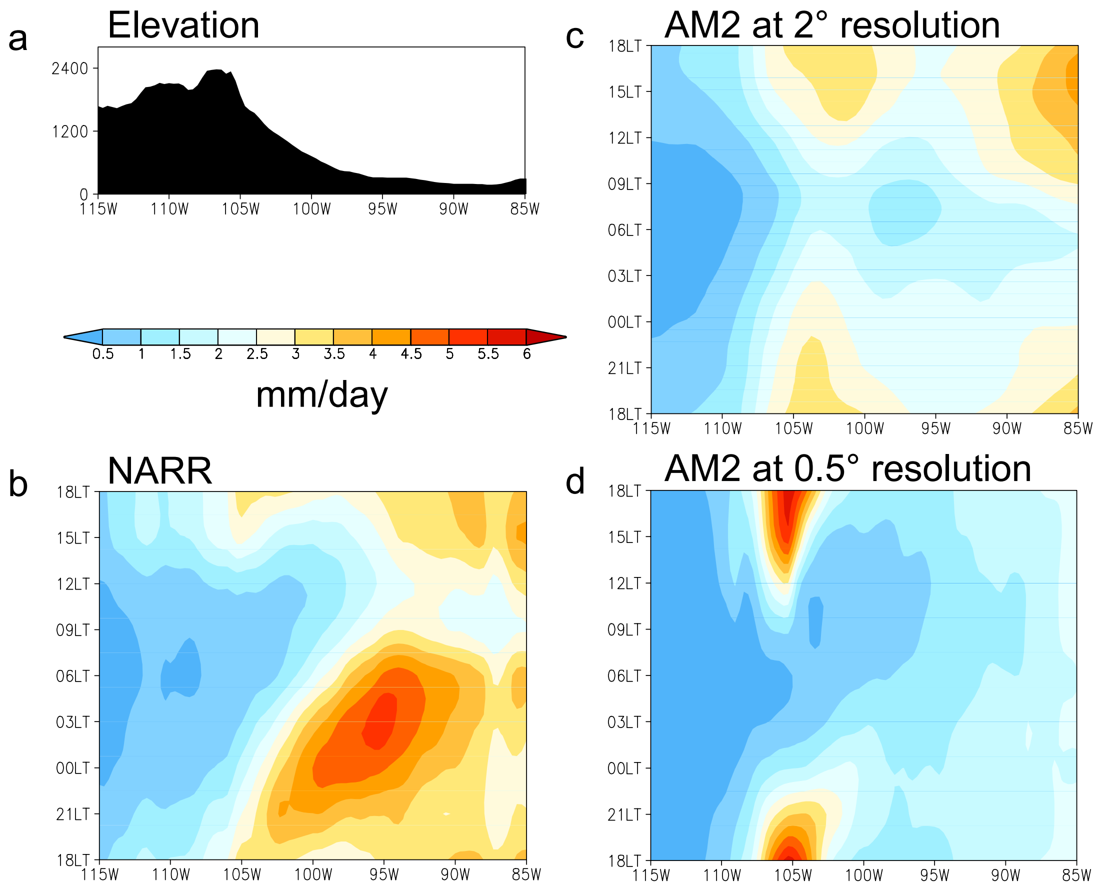

Figure 4. Diurnal cycles of summertime (May through August) precipitation averaged from 35-45°N from the NARR (b) and AM2 at 2° (c) and 0.5° (d) resolution. The diurnal cycles are plotted as a function of longitude with the mean surface elevation (units: m) displayed in panel (a). The composites are of 25 years of reanalysis data and of more than 10 years of AM2 integrated in climate mode at both resolutions.